Fibre based pump sources for ultra-fast transmission

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This report results from a contract tasking University of Southampton as follows: The contractor will develop pumped fiber lasers for ultra-broadband amplifiers and demonstrate an all-fiber amplifier with low nonlinearity. The research objectives are: (1) to explore feasibility of an Yb-doped fiber laser operating at 975 nm and demonstrate a compact 1 W fiber laser. The effort will involve developing a high power cladding pumped Yb-doped fiber alser operating at 975 nm ; (2) to use the developed 975 nanometer fiber laser as a pump source for a low nonlinearity, broadband, and Erbium-doped optical amplifier.

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I. Introduction

In this report we describe scientific activity within the project.

In the recent years EDFAs have become a key component in optical telecommunications and in numerous areas of laser applications. Compact and reliable high power amplifiers are in great demand due to rapidly growing needs of Internet and Information Super Highways.

Typically dense WDM (DWDM) systems require about 3 mW of signal power per channel. If number of channels is around 80, then EDFAs for DWDM systems should be capable of delivering ~300 – 500 mW of signal power. Such a high level of output power involves the use of high power pump sources with output power in the range of 2 - 4 W. Currently 980 nm pigtailed laser diodes is most widely used pump source. However power limit for reliable single-mode pigtailed laser diodes is around 200 mW and it is not clear wheatear LDs with higher output power will be available in near future. That is why the most common approach in developing of high power EDFAs is based on application of cladding pumped co-doped Er/Yb fibres and broad stripe 980 nm laser diodes.

Because of low core-to-cladding ratio effective pump absorption in cladding pumped fibre lasers is much lower than that in conventional, core-pumped schemes. That is why cladding pumped configuration normally utilizes Er/Yb co-doped fibers with typical effective pump absorption in the region of 0.2-5 dB/m (which corresponds to core absorption of ~ 200 dB/m). However fibre amplifiers based on Er/Yb co-doped fibres have narrower gain bandwidth in comparison to conventional Er-doped amplifiers. Therefore conventional, core-pumped Er-doped amplifiers can support greater number of channels provided sufficient pump power is available. This high demand for broad-band high power fibre amplifiers makes fibre lasers operating in the region of 980 nm highly sought after fibre-based devices.

Main difficulties associated with 976 nm fibre laser are large absorption/emission cross section and three level nature of Yb transition at this wavelength. That is why up to date there were very few results on successful demonstration of efficient 976 nm fibre laser.

In this project we have explored both core and cladding pumping approaches in development of high power fibre amplifiers for ultra-fast transmission.

II. High power Yb-doped fibre laser operating at 976 nm

IIa. Yb-doped cladding pumped fibre laser

Yb-doped fibre laser is the most obvious candidate for 980 operation. Fig.1 shows absorption and emission cross section of Yb ions in silica glass

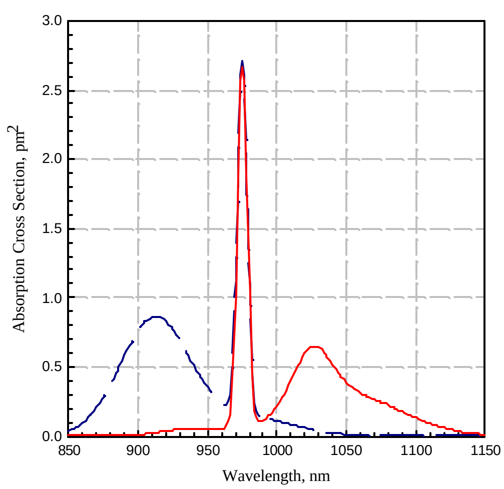


Fig. 1 Absorption and emission cross-sections of Yb ions in silica glass

It is clearly seen that there are two strong pump absorption bands around 920 nm and at 976 nm while emission cross section has strong peaks at 976 nm and around 1040 nm. Thus pumping at around 920 nm one can realize a 980 nm fibre laser. However owing to a three level nature of lasing transition at 980 nm this fibre laser should be carefully designed to avoid loss in an un-pumped section. Optimum efficiency of this laser is obtained when the residual pump power at the far end is just sufficient to reach transparency (zero gain) for the signal wave (except of course, if the residual pump is reflected back into the cavity).

The transparency power can be expressed as

$$P_{tr} = A_{eff} \frac{h\nu_p}{\eta_p(\sigma_e^s \sigma_a^p / \sigma_a^s - \sigma_e^p)\tau} \qquad (1)$$

where σ_e^s, σ_a^s, σ_e^p, σ_a^p - emission and absorption cross sections at signal and pump wavelengths respectively, A_{eff} is the core area, η - is the overlapping factor and τ is the upper level lifetime. In the case of Yb-doped 980 nm fibre laser with pump at 920 nm we have:

$\sigma_e^s = \sigma_a^s = 2.6 \cdot 10^{-20}$ cm^2 , $\sigma_a^p = 0.8 \cdot 10^{-20}$ cm^2, $\sigma_e^p = 0$, $\tau = 0.8$ ms and $\eta = 1.0$.

For a 6 μm core and in-core pumping $P_{tr} = 8$ mW. However in cladding pumped configuration (with 125 μm pump cladding diameter) this value goes up to 3.5 W. Figure 2 shows dependence of transparency power against pump cladding diameter. Results shown on Fig.2 clearly indicate that a practical cladding pumped 980 nm fibre laser should have cladding diameter of no more than 50-60 μm.

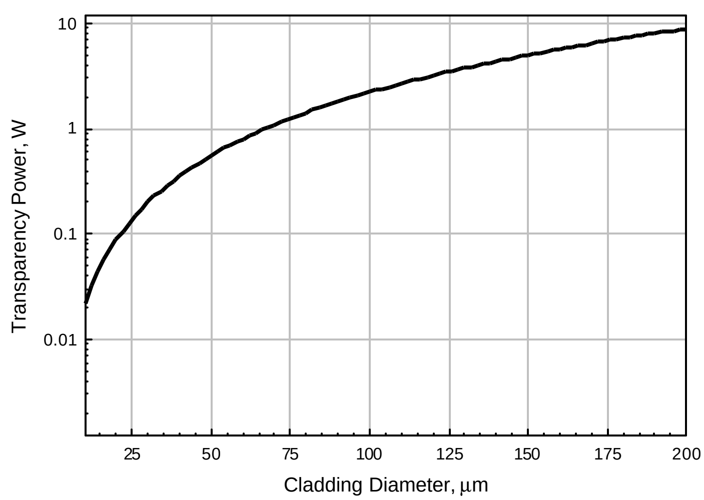


Fig.2 Dependence of transparency power on cladding diameter

However such thin cladding pumped fibres are very difficult (if not impossible) to handle and therefore this straightforward way looks impractical.

Another problem is associated with re-absorption of signal power at 980 nm and emission in the 1040-1080 spectral region. To prevent development of un-wanted ASE at 1040 nm one has to use spectral filtering in form of long period fibre grating or utilize spectral dependence of bend losses.

IIb. Experimental set-up and results

Experimental set-up is shown in Fig, 3. As a pump source we have used a beam-shaped diode bar operating at 915 nm. Cladding pumped fibre has a 150 μm cladding diameter and 40 μm core diameter. To prevent the laser to operate at the undesirable wavelength of 1060 nm the fibre length was kept as short as 80 cm. Feedback to the laser cavity was provided by a bulk grating orientated in such a way that radiation at 980 nm was feed back.

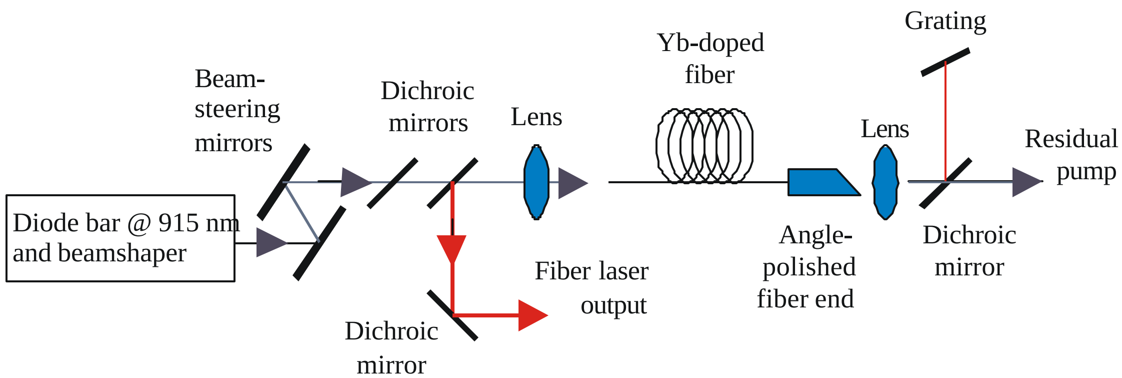
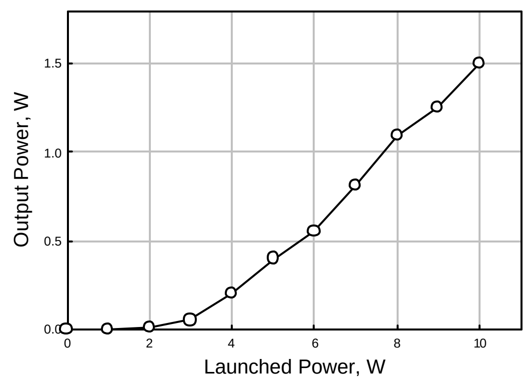


Fig. 3 Experimental set-up

With 12 W of launched pump power the laser produced 1.5 W of signal at 976 nm. Fig. 5 shows output spectrum and output power

(a)



(b)

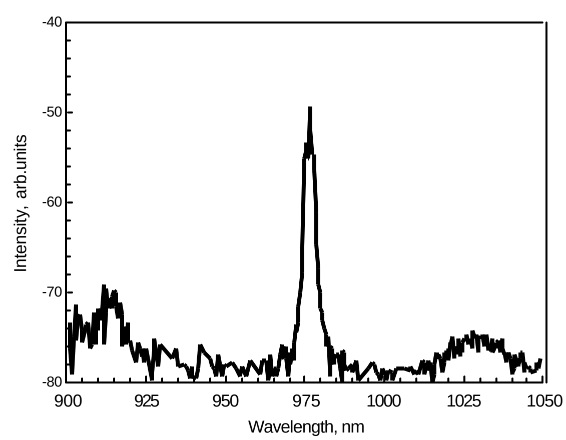


Fig.4 Output power vs launched power (a) and output spectrum (b) of Yb-doped fibre laser operating at 976 nm

The laser efficiency is about 15% in respect to launched power. This rather low efficiency can be easily explained by the fact that throughput pump power was about 5W so that absorbed power was just 5 W (for a 10 W of launched power). Relatively high threshold may be accounted for loss at lasing wavelength.

IIc. All glass cladding pumped fibre

In order to achieve high intensity of pump power retaining at the same time reasonable dimensions of doped fibre one can design an all-glass structure with a refractive index profile similar to that shown in Fig.5

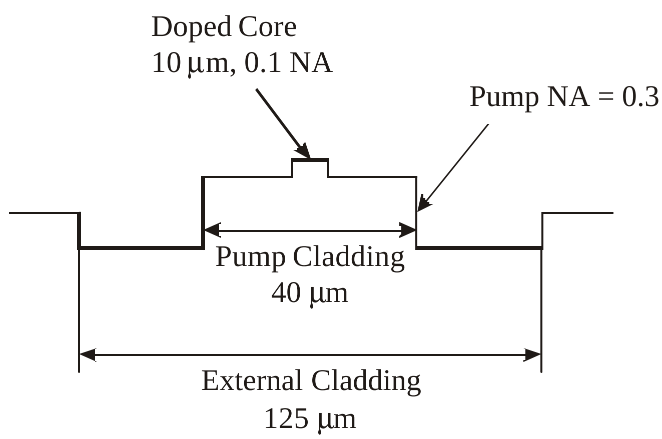


Fig.5 Refractive index profile of all glass cladding pumped fibre

Small cladding area of this fibre results in low transparency power (~ 200 mW) while core diameter of 40 µm is sufficient to launch more than 4 W of pump power.

Experimental realization of this fibre has encountered technical problems associated with difficulties to achieve high pump NA. Relatively low pump NA (~0.22) has resulted in low pump power launching efficiency (~ 10-15%) from commercially available pump sources. Low launching efficiency significantly reduces attractiveness of such fibre lasers

III. High power cladding pumped fibre laser and amplifiers

IIIa. High power fibre laser

First we present results on development of highly efficient Er/Yb co-doped fibre.

Erbium-ytterbium co-doped fiber (EYDF) was a conventional double-clad fiber, with a core for guiding the lasing light centered in a circular inner cladding that also served as a waveguide for the pump light. The core consisted of a phosphosilicate glass with a diameter of 12 µm and a numerical aperture of 0.18, resulting in a calculated cut-off wavelength of 2.7 µm with five modes supported at 1550 nm. The inner cladding was coated by a low-index UV-curable polymer outer cladding that provided a nominal numerical aperture of 0.48 for light in the inner cladding. The measured pump absorption was found to be ~2.7 dB/m at around 975 nm and ~2.0 dB/m at 915 nm. The high pump absorption allowed for a good efficiency for fibers as short as 1.4 – 2 m even in this cladding-pumped configuration. Short fibers are attractive for reducing the effect of various nonlinear effects, such as stimulated Brillouin scattering. We also measured the erbium core absorption at the 1535 nm peak to 60 dB/m.

The experimental set-up is shown in Fig. 6. Slightly different configurations were used, with single-ended pumping at 980 nm or 915 nm (Fig. 1a) and double-ended pumping at 915 nm (Fig. 6b). For 915 nm pumping, we used beam shaped diode bar from Optopower while for 980 nm pumping, a Polychrome laser system (Polaroid), combining eight broad-stripe diodes was used. It is to be noted here that the center wavelength of the Polaroid diode (980 nm source) shifts from 973 nm at threshold to 981 nm at maximum current. Pump beams were launched into the EYDF via dichroic mirrors and gradient-index lenses. The 4% reflecting bare fiber facets provided feedback for the laser. The output from the fiber laser was thus double-sided. This configuration is suitable for characterization of fiber lasers. For a more practical laser with a single-sided output, we could use a high-reflecting element in one end (e.g., a butted dichroic mirror or a fiber grating). Alternatively, a 4% reflecting end can be used together with a low-reflecting (e.g., angle-cleaved) fiber end to generate predominantly uni-directional output [3]. The dichroic mirrors at the input and output ends separated the laser output from the path of the pump beam. We separately measured the power of the three beams exiting the fiber.

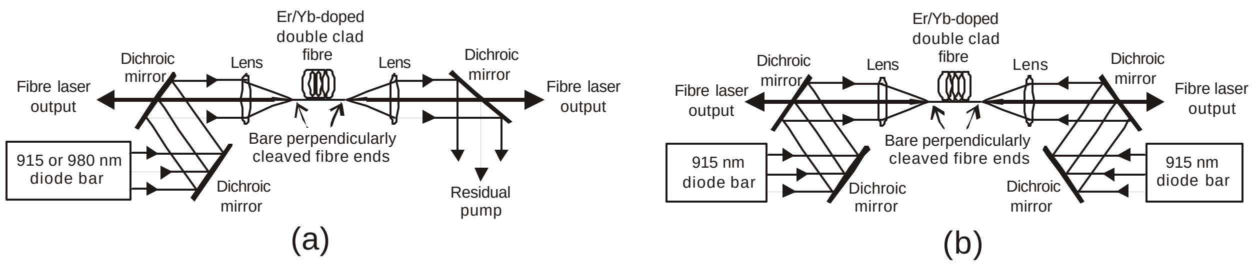


Fig. 6 Experimental set-up; (a) free running laser pumped by single 915 or 980 nm diode bar, (b) free running laser pumped in opposite ends by two beam-shaped 915 nm diode bars.

Figure 7a shows the total (double-ended) free-running laser output power vs. launched single-ended pump power for different fiber lengths between 1.5 and 4 m with 915 nm pumping, as well as for a fiber length of 1.4 m with 980 nm pumping. For the 915 nm pumping, the slope efficiency with a 1.5 m long fiber was lower than with longer fibers because of incomplete pump absorption. It then increased before it gradually decreased again for longer fibers. The highest output power was 6.0 W, which was reached both with 2 and 2.5 m long fibers. We attribute the decrease to excess propagation losses: As the fiber gets longer, excess losses start to surpass the benefits of increased pump absorption. Figure 7b shows how the pump transmission depends on the pump power for the same set of parameters as used in Fig. 7a. The 1.5 m long fiber emitted at 1536 and 1542 nm simultaneously. The wavelength then shifted to longer wavelengths with longer fiber, to ~1550 – 1560 nm for the 4 m long fiber, as a result of increased Er^{3+} re-absorption. The performance with 980 nm pumping was worse than that with 915 nm pumping, with a maximum output power of 3.5 W. Again, the laser emitted simultaneously at 1536 and 1542 nm.

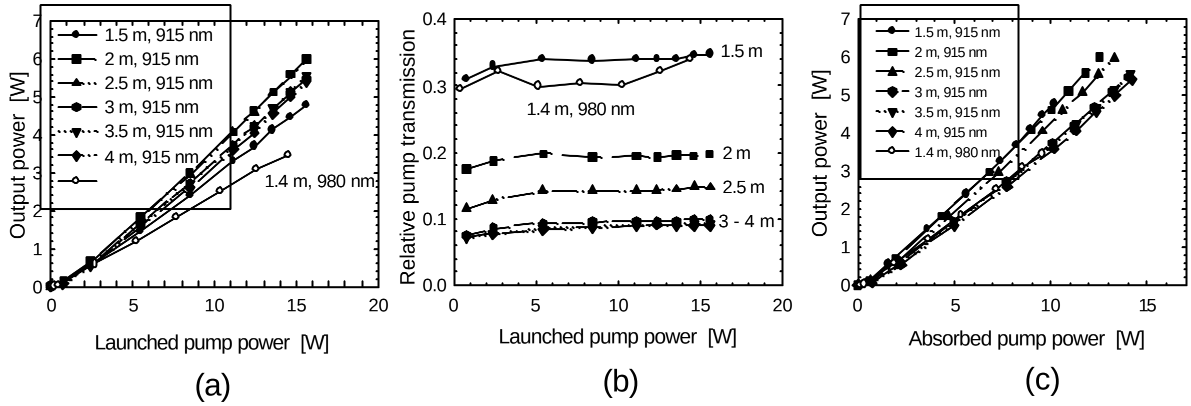


Fig. 7 (a) Output power (double-ended) as a function of launched pump power, (b) transmitted pump power vs. launched pump power and (c) output power (double-ended) vs. absorbed pump power; for different fiber lengths with single-ended pumping at 915 nm and 980 nm.

In order to differentiate the influence of incomplete pump absorption on slope efficiency from genuine loss mechanisms, Fig. 7c plots the double-ended laser output power vs. absorbed pump power for the configurations used for Fig. 7a. As we expect, the shortest fibers now have the highest slope efficiency with 915 nm pumping, since the excess propagation losses would be smaller in a shorter fiber. The slope efficiency with respect to launched power peaked for fiber lengths of 2 and 2.5 m, with a maximum value of 40%. The slope efficiency with respect to absorbed power reached 49 – 50% for 1.5 – 2 m long fibers. It then decreased for longer fibers, to 41% for a 4 m long fiber. With 980 nm pumping of the 1.4 m long fiber, the slope efficiency was 38% with respect to absorbed pump power.

Quenching via energy-transfer up-conversion is a known problem in erbium-doped fibers, leading to a certain fraction of the Er-ions being impossible to excite and un-saturable absorption [4]. Though Yb co-doping counteracts Er-quenching [5], it may still occur in our EYDF, especially since the Er-concentration is quite high. We tentatively attribute the reduction of slope efficiency with fiber length to Er-quenching. Erbium quenching could also account for the non-perfect quantum slope efficiency. Our highest slope efficiency of 50% corresponds to a quantum slope efficiency of 84%. However, the details of how energy quanta are trapped by the quenched centers are unknown, preventing us from quantifying this process. We note that several other parasitic processes are possible in EYDFLs, e.g., cumulative energy transfer from ytterbium to high-lying erbium states [5]. We do not know why 980 nm pumping is less efficient than 915 nm pumping in our fiber, However, the 980 nm pump interacts more strongly with the gain medium than a 915 nm pump does. Loss mechanisms, and especially nonlinear loss mechanisms (e.g. cumulative transfer), may then be expected to have a greater impact with 980 nm pumping.

The energy transfer efficiency from ytterbium to erbium impacts on the overall slope efficiency, too. Since the pump excites the Er^{3+}-ions indirectly via energy transfer from Yb^{3+}-ions, more Yb^{3+}-ions are excited at higher pump levels. This reduces the pump absorption and thus the laser output power. If the energy transfer is poor, a large number of Yb^{3+}-ions needs to be excited in order to generate a certain rate of energy transfer. Returning to Fig. 7b, we see that there is some bleaching at low pump powers with 915 nm pumping, as the pump transmission increases with pump power. Higher pump powers lead to even more bleaching (at least for a fiber length of 1.5 m), but the change is not so large. For 980 nm pumping, the decrease in transmission at intermediate pump levels can be understood as a change of pump wavelength with pump power – at intermediate powers the pump wavelength is better matched to the Yb^{3+} absorption peak. However, especially with 980 nm pumping, the heating of the EYDF with stronger pump power may also affect the absorption, making the bleaching difficult to interpret.

Bleaching of the pump absorption can ultimately limit how much power an EYDFL can generate. Figure 7a does indicate a tendency for the power to roll over with 980 nm pumping, perhaps because of the drifting pump wavelength though the data is uncertain. However, with 915 nm pumping, the curves show no sign of the output power rolling over as the pump power increases.

Furthermore, the bleaching in Fig. 7b is small even at high powers. This suggests that the output power could be even higher with stronger pumping. To investigate this, we pumped an EYDFL with two 915 nm beam-shaped diode bars in opposite ends of a 4 m long fiber, as illustrated in Fig. 6b. Figure 8 shows the laser output power vs. total launched pump power. The maximum output power is 15.8 W, still reached without any signs of rollover. We then changed the fiber configuration in order to improve the pump absorption and attained an output power of 16.8 W.

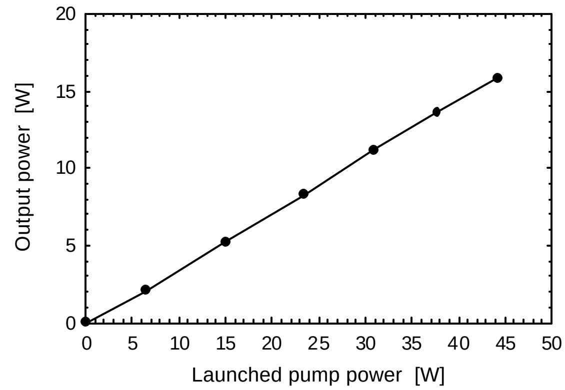


Fig. 8 Output power (double-ended) as a function of launched pump power for double-ended pumping at 915 nm.

IIIb. Cladding pumped Er/Yb fibre amplifier

Experimental configuration is shown in Fig.9. In our experiments we have used a 5 m long Er/Yb co-doped fibre

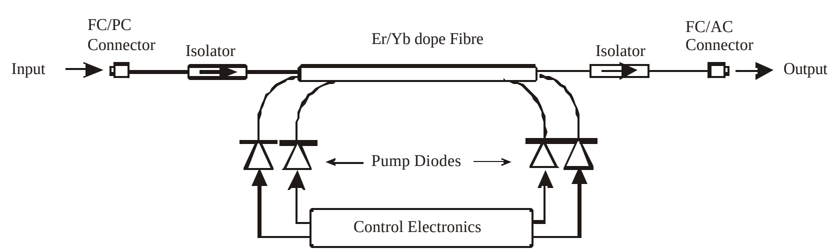


Fig.9 Configuration of an Er/Yb co-doped fibre amplifier

Pump power from 4 pump diodes were launched via an auxiliary pump fibre side-spliced to a doped fibre as it is shown on Fig.10.

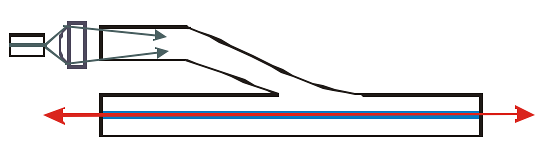


Fig.10 Schematic of pump coupler

Insertion loss of this couplers was approximately 0.8 dB, so with 8 W of pump power available from all 4 diodes we were able to launch 7 W of pump power at 915 nm. Pump power absorption was 10 dB so with ~ 6 W of absorbed power we have obtained 2 W of amplified signal. (Note that due to single-pass nature of fibre amplifiers its efficiency was found to be 20% lower than that of fibre laser). We have not observed any detrimental nonlinear effects.

Fig.11 shows gain profile obtained at different levels of input signal power. Gain spectrum was taken by scanning of weak signal across gain band. Because of high output power gain spectrum is flat even when level of input power as low as –3 dBm

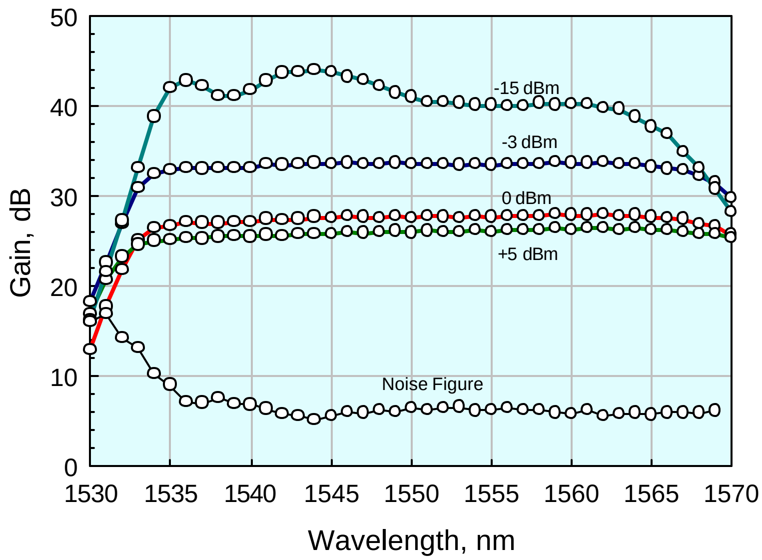


Fig. 11 Gain spectrum and noise figure of a high power, cladding pumped Er/Yb fibre amplifier

Relatively low pump intensity in cladding-pumped devices (in compare to core-pumped) results in high noise figure and it is one of the weaknesses of cladding pumping technology. In our amplifier noise figure was below 6 dB.

IV. Summary

We have experimentally investigated two approaches in development of high power amplifiers for ultra-high bit rate transmission.

First approach is based on application of an Yb-doped cladding pumped fibre laser operating in the region of 980 nm i.e. within the absorption band of Er ions in silica glass. Our results clearly indicate feasibility of fibre lasers operating at this wavelength. However we have found that with current technology overall efficiency of such lasers is low (~ 20%) and they are unable to compete with advanced laser diodes operating at the same wavelength.

Second approach is based on application of cladding pumped technique. We have developed a highly efficient Er/Yb co-doped fibre with efficiency of 51%. We have also demonstrated a high power amplifier capable of delivering more than two watts of optical power in the region of 1550 nm. Gain bandwidth of developed amplifier is 1535-1565 nm i.e. broad enough to support more than 75 channels with 50 GHz channel spacing

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